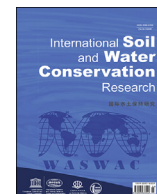




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## Original Research Article

## Small dams/reservoirs site location analysis in a semi-arid region of Mozambique

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## ABSTRACT

The water crisis is one of the biggest human problems in developing countries, especially in semi-arid regions where it can form an obstacle to irrigation and cultivation, cattle raising and people's survival. The construction of small dams/reservoirs are a possible solution to remediate this problem. These infrastructures must be located in suitable areas to be successful. This study aimed to find the most suitable locations for small dams/reservoirs in the Tete province region, Mozambique, which has a pronounced water deficit. A Geographical Information System (GIS) based approach was used to implement a multi-criteria evaluation (MCE) analysis through an Analytic Hierarchical Process (AHP), which included local experts' consultation. Three main categories of suitability were identified: "Not suitable" (15% of total area), "Modestly suitable" (78%), and "Suitable" (7%). We found that 35 of the 38 (92%) abandoned small dams/reservoirs were in areas classified as "Modestly suitable" confirming the robustness of our model. We also found that most of the dams/reservoirs currently operating (78%) and planned (73%) are in modestly suitable areas.

This finding suggests that the decision to construct dams/reservoirs may not have considered the most critical suitability factors identified in this study. More data and/or additional criteria are required for the full understanding of finding out why so many dams/reservoirs failed before building new ones to address the population's water needs in the region.

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## 1. Introduction

Water is the basis of life and livelihoods since it supports the health of ecosystems and is the fundamental element for sustainable development (Guppy & Anderson, 2017). Its availability and storage are useful for drinking, field crop irrigation, and economic development (Raza, Shafique, Sikandar, Ahmad, & Shah, 2018). Hence, the United Nations recognized ensuring water security as a sustainable development goal (SDG) (Goal 6) (Gain, Giupponi, & Wada, 2016). However, many people worldwide do not have secure access to suitable water to meet their most basic needs (Detoni & Dondoni, 2008; UNICEF-WHO, 2019). The lack of water resources is likely to be one of the biggest human problems in the next decades (Rezaei, Rezaie, Nazari-Shirkouhi, Reza, & Tajabadi, 2013; Vörösmarty, Pahl-Wostl, Bunn, & Lawford, 2013).

Climate change will significantly impact the hydrological regime, water availability, and quality by increasing the frequency and severity of droughts and floods, rainfall variability, and higher temperatures (Luhunga, Chang'a, & Djolov, 2017). Thus, there is a great concern that climate change could worsen the water resource crisis in areas with water scarcity (Abu-Allaban, El-Naqa, Jaber, & Hammouri, 2015; Malinowski & Skoczko, 2018). Projections for Africa by 2020, as a consequence of climate change, point to an increase in water stress with a reduction in agricultural incomes of 50% in some regions, severely compromising the access to food (Ammar, Riksen, Ouessar, & Ritsema, 2016).

Water scarcity is a critical issue in many developing countries (Ibrahim, Rasul, Hamid, Ali, & Dewana, 2019). Particularly in arid and semi-arid areas where evaporation exceeds precipitation, water scarcity affects livelihoods and food security since in the majority of the available water comes from the rain during the rainy season or the groundwater close to the land surface (Abdalla et al., 2017).

The need to have a continuous and stable water supply for

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human activities implies building dams and/or reservoirs to store water during the rainy season and use it in the drought season (Sayl, Muhammad, Yaseen, & El-shafie, 2016). Dams are transverse barriers to the direction of the flow of a water course to accumulate or raise the level of the water body (Ghazal & Salman, 2015). A reservoir is an artificial water body usually created in a river valley due to water-retaining constructions for accumulation and storage of water (Nagy, Asante-Duah, & Zsuffa, 2002). The construction of dams/reservoirs may provide water supplies for human needs and livestock, small-scale irrigation, and may play an important factor in improving the livelihoods of rural populations (Senzanje, Boelee, & Rusere, 2008; World Bank, 2007). Small dams/reservoirs have the advantage of being operationally efficient, flexible, close to potential users, and require relatively fewer issues for management (Keller, Sakthivadivel, & Seckler, 2000). Experiences with small and medium-size dams demonstrate that these contribute significantly to rural poverty reduction by increasing agricultural productivity and household food security, diversifying local economies and improving local incomes (World Bank, 2007).

In general, the process of selecting the location for the installation of dams/reservoirs is carried out through empirical knowledge and/or according to political interests (Al-Ruzouq, Shanableh, Yilmaz, et al., 2019). An imprecise assessment of the dam/reservoir site and below recommended standards can have harmful effects in the long run and result in incalculable negative impacts on the environment and livelihoods of the local population (Behera, 2013). The combination of Geographic Information Systems (GIS) and Remote Sensing (RS) enables time savings and containment of financial expenses by providing reliable and up-to-date information for water resource management (Mugo & Odera, 2019). These techniques play a fundamental role in identifying potential sites for water storage infrastructure combined with hydrological analysis and modeling (Ahmad & Verma, 2018); RS technology because it allows covering large and inaccessible areas in a short time and different resolutions, providing different environmental and hydrologic parameters for the analysis, and GIS tools because it integrates all these thematic layers together (Elbeih, 2015).

GIS and RS through approaches together with multi-criteria evaluation (MCE) techniques, such as Analytic Hierarchy Process (AHP), Boolean logic, fuzzy logic, Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), among others, allow the articulation and aggregation of geospatial information to perform dam site suitability mapping and analysis (Al-Ruzouq, Shanableh, Yilmaz, et al., 2019; Jozaghi et al., 2018; Lee, Hyun, Lee, & Lee, 2020).

The selection of modeling techniques used to analyze dam/reservoir suitability varies according to the available data, expertise and local context. When using MCE analysis, several factors that affect dam/reservoir site suitability can be considered, such as the character of foundations, topography, hydrological aspects, spillway capacity, availability of construction materials, submerged land value, accessibility and living facilities (Duggal & Soni, 1996). Al-Ruzouq, Shanableh, Yilmaz, et al. (2019) provide a comprehensive list of factors and respective techniques used in dam suitability studies in many regions of the world, such as Iraq, Pakistan, Sweden, India, and Malaysia. Many other studied locations can be found in the literature, such as the United Arab Emirates (Al-Ruzouq, Shanableh, Yilmaz, et al., 2019), Iran (Jamali, Randhir, & Nosrati, 2018; Yasser, Jahangir, & Mohammad, 2013), South Korea (Choo, Ahn, Yang, & Yun, 2017), among other locations. However, studies are rare for Mozambique's semi-arid region, which struggles significantly against water scarcity. This study fills this gap by providing the first dam/reservoir suitability mapping study for a semi-arid region in Mozambique. This aspect is crucial since one of the strategic and priority objectives of the Mozambican government is to reduce the vulnerability of rural communities to climate

risks and natural disasters through the rehabilitation and construction of 80 small dams/reservoirs to support irrigation for small producers and increase production in drought agricultural areas and improve food security (AR, 2020). This paper aims to identify the most suitable dam/reservoir sites for the semi-arid zone of the Tete Province, Mozambique. Specifically, we aim to:

- Identify the biophysical and socioeconomic factors based on a literature review;
- Use an AHP with local expert opinion to create a dam/reservoir suitability map; and
- Validate the results obtained through the abandoned dam/reservoirs and provide an outlook on the current operational and planned dam/reservoir infrastructure.

Results are expected to contribute with relevant information to support the Southern African Development Community water protocol signed in Johannesburg in 2002. Within this protocol, Mozambique established a regional agreement among the countries in which an action plan for drought mitigation has been delineated, including measures to expand the access to drinking water to populations, particularly in arid and semi-arid areas, and the creation of infrastructures to increase the storage capacity and reduction of water loss (MICOA, 2005).

## 2. Study area

The study area is in the south of the Tete province, Mozambique, in the districts of Cahora Bassa, Changara, Chiuta, City of Tete, Luenha, Magoe, Maraza, Moatize and Mutarara covering an area of 48454.4 km<sup>2</sup>, considered one of the semi-arid regions of Mozambique (Fig. 1). According to the census, there were 1,070,712 people living in these districts in 2017 (INE, 2019). The region is inhabited mainly by a rural population whose survival depends fundamentally on agriculture. Agriculture is the largest sector of the country's economy. About 80% of households are involved in the agricultural sector, contributing up to 29% of the Gross Domestic Product (GDP) (FAO, 2016).

The population's agricultural practice and food security are affected by problems related to climate change problems, such as drought, floods, and cyclones (Engelman, 2009). The vulnerability of this region is partly due to irregular precipitation since the rainy season often does not start as predicted resulting in unpredictable seeding seasons (Fig. 2). Rainfall events concentrate in very short periods causing soil erosion by the surface runoff (MICOA, 2005). The southern region of the Tete Province, north of Sofala and Manica and Inhambane and Gaza provinces are the most critical regions with a high-risk drought level (INGC, 2017) (Fig. 3).

The lack of water in Tete's semi-arid region is related to the severity of climate and to the lack of infrastructures to store water. There is insufficient groundwater extraction through the excavation of artesian wells allied to a low quantity of dams/reservoirs with the capacity to meet population's demand. Recently, the National Institute of Disasters showed a great interest in implementing the Johannesburg agreement and intends to find better ways to increase water availability for inhabitants, crop and livestock production by creating dams/reservoirs in the best available areas. Due to the water scarcity in the region, the development of artificial water storage is necessary and mandatory for ensuring reliable water supply during periods of reduced natural water availability (droughts) as well as for retaining excessive water during periods of floods (World Bank, 2007).

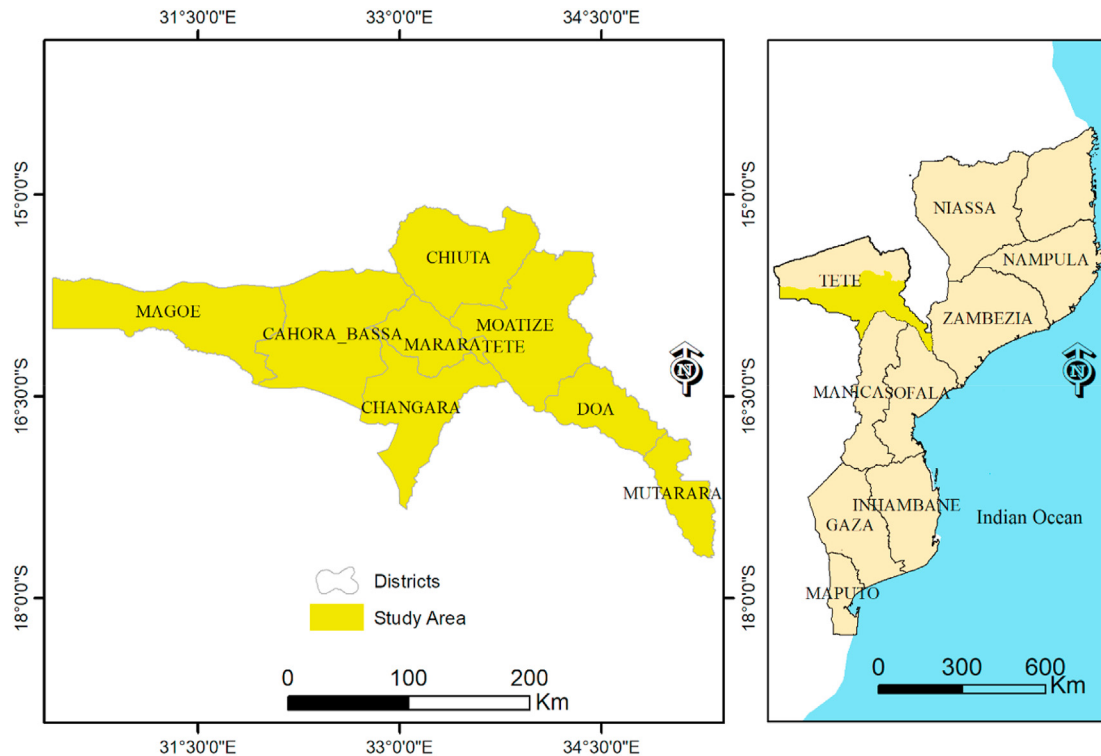


Fig. 1. Geographic location of the study area.

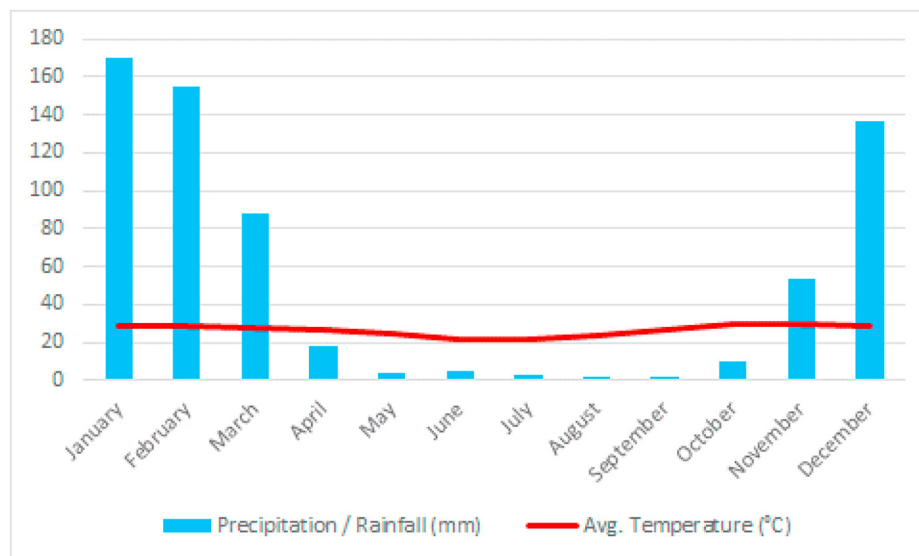


Fig. 2. Tete average rainfall and precipitation (Source: <https://en.climate-data.org>).

### 3. Data and methods

#### 3.1. Methodological approach

Multi-Criteria Evaluation (MCE) methods provide a framework for facilitating decision making through information exchange and negotiation among stakeholders (Kiker, Bridges, Varghese, Seager, & Linkov, 2005; Malczewski, 2006). An approach involving several geospatial operations was adopted to determine the suitability of siting small dams/reservoirs based on multiple criteria and an Analytic Hierarchy Process (AHP) (T. L. Saaty, 1986) (Fig. 4).

#### 3.2. Identification of criteria

A literature review was carried out to determine the most relevant criteria to locate dams/reservoirs. This exercise included identifying factors, constraints, and exclusionary areas considering Tete's region specific biophysical and socioeconomic conditions and data availability (Table 1).

#### 3.3. Data sources and preprocessing

Several spatial datasets in vector and raster formats and with

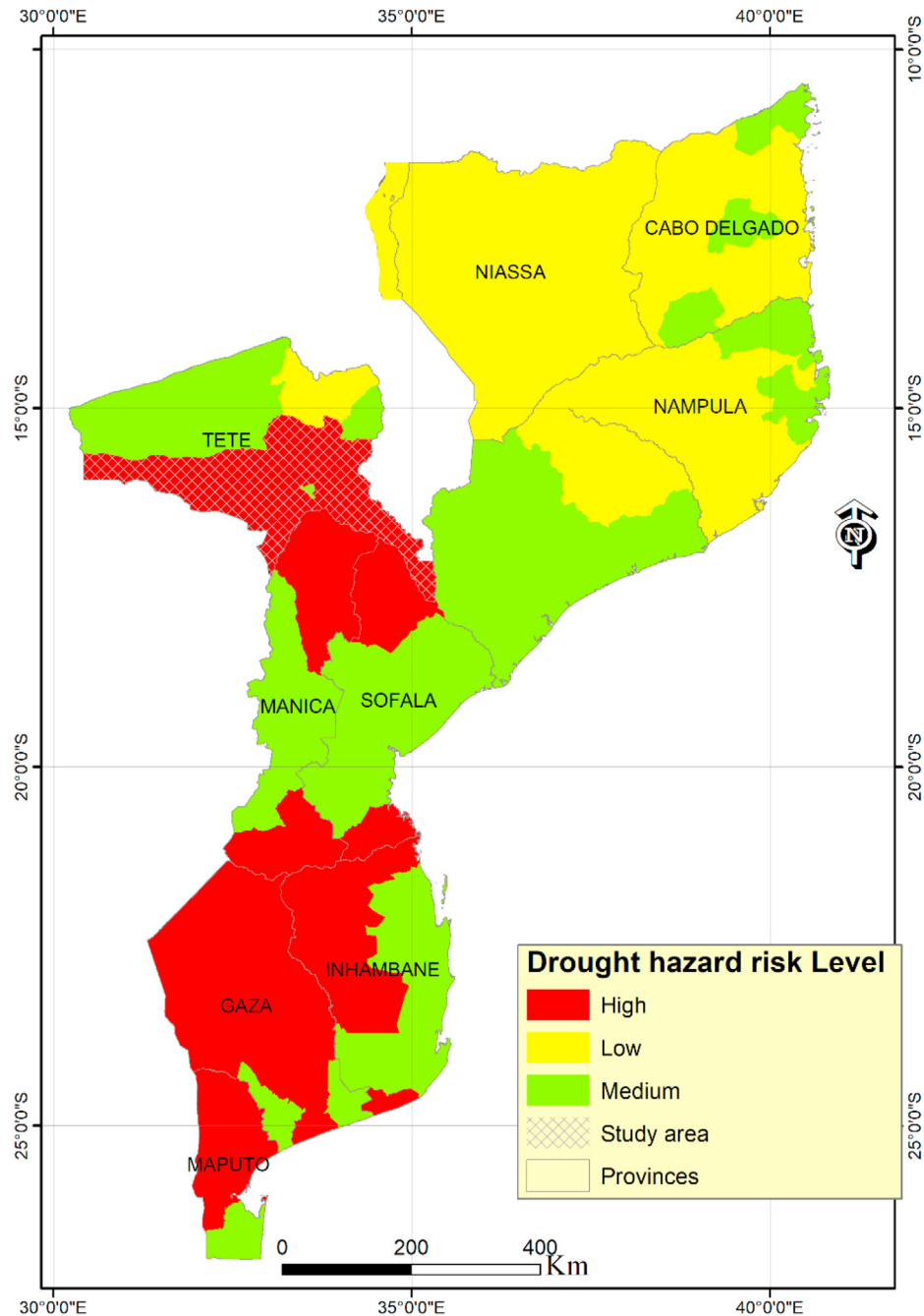


Fig. 3. Mozambique drought hazard risk level (Adapted from INGC, 2017).

different scales and resolutions were used in the study to create the factors to be included in the MCE modelling (Table 2).

The study area dataset was obtained from CENACARTA (CENACARTA, 1997). The lineament structure was derived using the lineament extraction algorithm in PCI Geomatica software (PCI, 2018). Because of the ease in distinguishing between types of rocks and minerals, band 6 of the Landsat 8 satellite was used to map these geological structures (Aretouyap, Billa, Jones, & Richter, 2020; Epuh et al., 2020). Short-wave infrared (SWIR 1) and band 6 of the Landsat 8 image for 2016 were downloaded from the EarthExplorer platform (United States Geological Survey, n.d.) using the following path and row: 167/72 (12-Aug), 168/72 (19-Aug), 168/71 (28 Aug), 169/71 (26-Aug) and 170/71 (17 Aug). The distance to

roads and villages were obtained using the Euclidian distance tool of ArcGIS (ESRI, 2017). A Digital Elevation Model (DEM) (NASA JPL & NASA/METI, 2012) with a resolution of 30 m was obtained for the Tete Region with elevation ranging from 0 to 1545 m (above sea level). The slope was derived from the DEM using the surface tool of the Spatial analyst extension of ESRI ArcGIS software (ESRI, 2017). Soil data for the study area were obtained from the National Soil map, scale 1:1000000 (DTA-INIA, 1995). The rainfall data based on the mean annual rainfall were obtained from WorldClim (Fick & Hijmans, 2017). WorldClim is a set of global climate layers (gridded data) with a spatial resolution of 1 km<sup>2</sup>. The data for this criterion were derived from the DEM using the hydrology extension of ArcGIS software (ESRI, 2017), after proceeding with the sink fill,

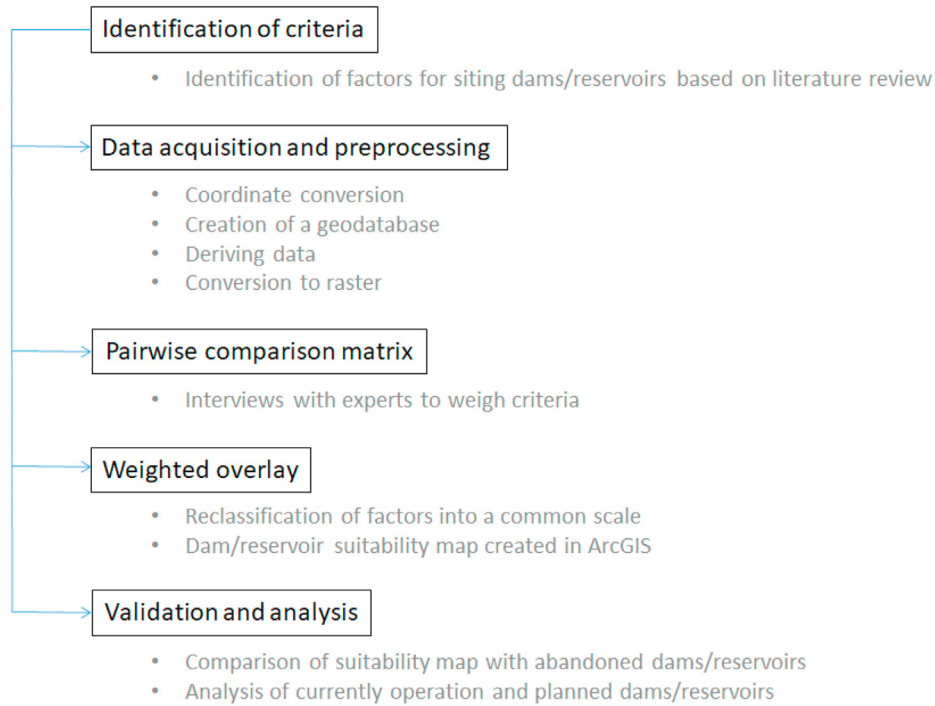


Fig. 4. Flowchart of research methodology.

**Table 1**  
Used criteria and rationale.

Criteria	Rationale	References
Elevation	Elevation influences the location of dams/reservoirs since it affects the water accumulation and movement. Lower elevations are preferable to higher elevations.	Al-Ruzouq, Shanableh, Merabtene, et al. (2019)
Slope	Higher slopes have a higher risk of landslides and put more pressure on the foundation of the infrastructures. The higher the slope in the construction site the lower the potential for storing water and sediment, meaning that lower slopes have more storage volumes.	Ahmad and Verma (2018)
Distance to roads	The presence of roads and settlements close to the proposed sites will reduce the costs of water transportation.	Othman et al. (2020)
Rainfall	Is the primary source of runoff water recharge. Rainfall intensity and its distribution are some of the pre-requisites for designing a water harvesting system.	Prinz and Singh (2000)
Lineaments	Lineaments are linear features on the Earth's surface which reflect the geological structure such as faults or fractures. Areas near lineaments are potential weakness zones for installing infrastructures.	(Elbeih, 2015; Othman et al., 2020)
Distance to villages	The closer dams/reservoirs are to populations the lower will be the costs of water transportation.	Mugo and Odera (2019)
Land use land cover	Areas proposed for constructing of dams/reservoirs should be in or close to agricultural land to reduce the distances of farmers searching for water and the cost of transferring water from the reservoir to agricultural land. In addition, the primary objective of the dam/reservoir proposed for the study area is to assist crops field irrigation.	Mugo and Odera (2019)
Soil type	The type of soils is influenced by its texture, structure and depth which determine soil infiltration rates and the amount of runoff.	Jha, Chowdary, Kulkarni, and Mal (2014)
Stream density	Provides the necessary runoff water for dam/reservoir function, since different drainage network levels indicate different amounts of runoff water when the streams are upper stream tributaries and main downstream streams. Areas with high drainage density are ranked higher in suitability compared to areas of low drainage.	(Jha et al., 2014; Mbilinyi, Tumbo, Mahoo, & Mkilamwinyi, 2014)

flow direction identification, calculation of the flow accumulation and definition of the stream network. Stream density was calculated using the Spatial Analyst Density tool in ArcGIS (ESRI, 2017).

After acquiring and pre-processing all data, these were converted into raster and stored in a spatial geodatabase using a World Geodetic System (WGS) 84, Universe Transverse Mercator (UTM) coordinate system with 30 m spatial resolution.

### 3.4. Pair-wise comparison matrix

AHP was originally developed by (T. L. Saaty, 1986) and has been applied to many fields (Choudhary & Shankar, 2012; Colak, Memisoglu, & Gercek, 2020; Dedeoğlu & Dengiz, 2019; Martins,

Silva, & Cabral, 2012). The implementation of AHP involves the creation of a comparative decision-making preference matrix and determining the factor weights (T. L. Saaty, 1986). The pairwise comparison is applied on all criteria using the fundamental scale proposed by Saaty (1986) (Table 3). In the comparison process, a scale of numbers is used indicating how many times more important one element is over another element with respect to the criterion or property to which they are compared (T. L. Saaty, 2008). This method enables a decision-making group to focus on areas of agreement and disagreement when setting criterion weights (Drobne & Lisec, 2009).

A structured interview was undertaken with four local experts with a background in geology, water resource management,



**Table 2**  
Data used and their sources.

Data	Description	Scale/Spatial resolution	Source
Study Area	Polygon with boundary of semi-arid region of Tete Province	1:250000	CENACARTA (CENACARTA, 1997)
Band 6 of Landsat 8 OLI (2016)	Shortwave infrared band used for lineament extraction (Landsat scene 170/72)	30 m	USGS (USGS, 2016)
Roads	Polylines data with existing roads		CENACARTA (CENACARTA, 1997)
Villages	Point data with the main settlements	1:250000	CENACARTA (CENACARTA, 1997)
Digital Elevation Model (DEM)	Raster dataset with elevation	30 m	ASTER GDEM (NASA JPL & NASA/METI, 2012)
Land use/Land Cover	Polygons with land use and land cover categories (2018)	–	MITADER (MITADER, 2018)
Soil	Polygons with soil types	–	DPA-INIAM (DTA-INIA, 1995)
Rainfall	Raster dataset showing the mean of rainfall	1 km <sup>2</sup> Global Climate data	Fick and Hijmans (2017)
Dams/reservoirs	Point data with the dams/reservoirs	–	ARA-ZAMBEZE (ARAZAMBEZE, 2020)

**Table 3**  
Relative importance. Adapted from Saaty (1986)..

Intensity of relative importance	Definition	Explanation
1	Equal importance	Two criteria contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one criterion over another
5	Strong importance	Experience and judgment strongly favor one criterion over another
7	Very strong or demonstrated importance	A criterion is favored very strongly over another; its dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one criterion over another is of the highest possible order of affirmation
2, 4, 6, and 8	Intermediate	Can be used if necessary

hydrology, and civil engineering, respectively. The interview, carried out in January 2020, aimed at exploring their opinions regarding the relative importance of the selected criteria for dam/reservoir siting and the creation of the pairwise comparison matrix. The weighted vector of this matrix was normalized, and the normalized weight vectors were obtained according to the relative level of importance of the criteria used (T. L. Saaty, 1986). A consistency ratio (CR), which measures how consistent the judgments have been relative to large samples of purely random judgments, is computed from the resulting normalized vector values (T. L. Saaty, 1986) (Eq. (1)). If the CR is over 0.1, then the judgments should be considered untrustworthy.

$$CR = CI / RI \quad (1)$$

where CR is the consistency ratio, CI is the consistency index (Eq. (2)), and RI represents a random consistency index derived from a sample of randomly generated reciprocal matrixes (R. W. Saaty, 1987; T. L. Saaty, 1986).

$$CI = (\lambda_{\max} - n) / (n - 1) \quad (2)$$

where  $\lambda_{\max}$  is the principal Eigen value, i.e. the value obtained from the summation of products between each element of the Eigen vector and the sum of the columns of the reciprocal matrix, and n is the number of factors.

### 3.5. Suitability index

After determining the weights, all the criteria were reclassified into a common evaluation scale before performing the weighted overlay analysis in ESRI's ArcGIS Spatial Analyst (ESRI, 2017). Five classes of suitability were used in this process: "Highly unsuitable"; "Not suitable"; "Modestly suitable"; "Suitable" and "Highly suitable". Highly faulted areas are not suitable for dam/reservoir construction, so dam sites should be located at least 100 m away from lineaments (Othman et al., 2020). The lineaments were reclassified in two classes of suitability; less than 100 m ("Highly unsuitable")

and more than 100 m ("Highly suitable"). Soil classes were reclassified according to their level of suitability (DTA-INIA, 1995). All the remaining input rasters were reclassified using Natural Breaks (Jenks) classification method available in ArcGIS. This method identifies real classes within the data, creating accurate representations of trends in the data (Karlsson, Kalantari, Mörtberg, Olofsson, & Lyon, 2017; Oswald Beiler & Treat, 2015).

In this study, we used a Weighted Linear Combination (WLC), which is based on a weighted average that can easily be understood and implemented within a GIS environment using map algebra operations and cartographic modeling (Chen, Zhang, & Zhu, 2011; Malczewski, 2000). By obtaining the summation of the product of the relative importance weight (percentage of influence) of each criterion with its standard suitability score, a suitability index was determined (Eq. (3)):

$$SI = \sum w_i s_i \quad (3)$$

where SI is the suitability index,  $w_i$  corresponds to the relative importance of criterion  $i$  and  $s_i$  is the standardized suitability score of criterion  $i$ .

### 3.6. Analysis of current and future situation

In the study area, a total of 38 dams/reservoirs were abandoned, 37 are in use, and 15 are in the process of being built (ARAZAMBEZE, 2020). The infrastructures' georeferenced points were overlaid with the suitability map to check the coincidence level between these data sources providing an outlook of the water infrastructure in the region.

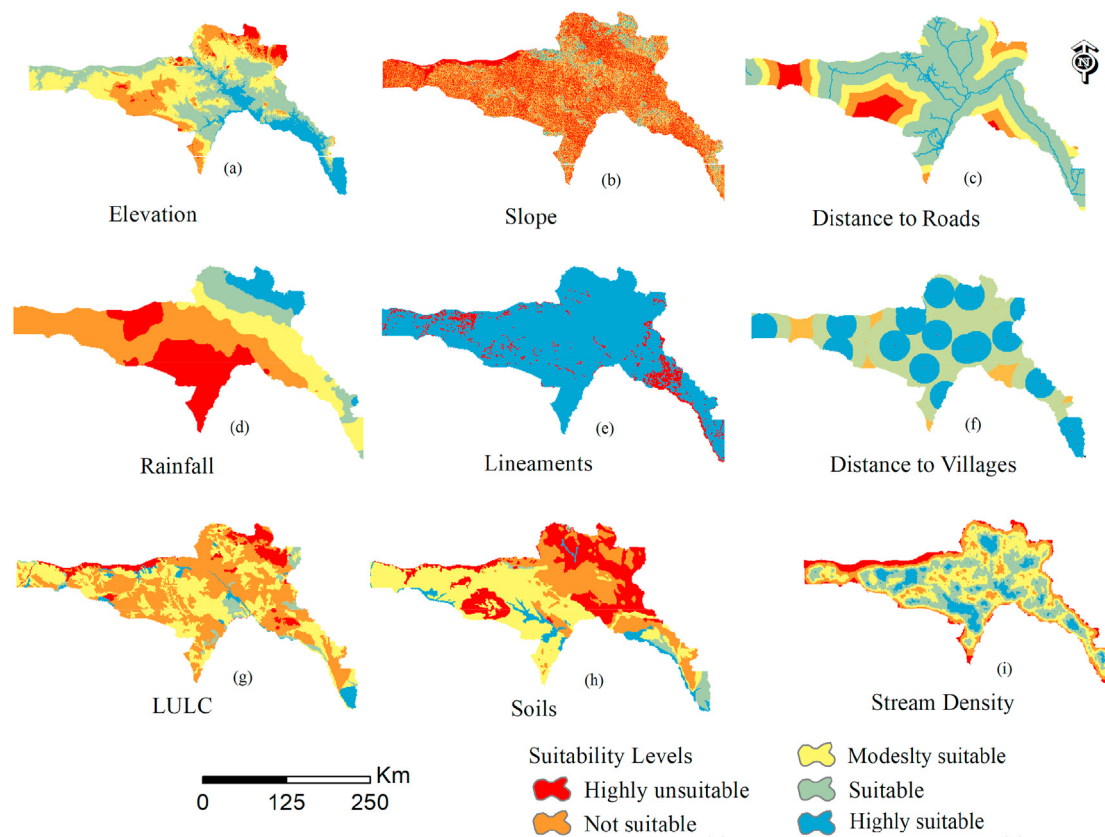
## 4. Results

### 4.1. Suitability criteria and reclassification

The nine criteria were reclassified using the suitability level presented in Table 4. This process resulted in nine maps presented in Fig. 5.

**Table 4**  
Site selection criteria used and level of suitability.

Criteria	Suitability Level				
	Highly unsuitable	Not suitable	Modestly suitable	Suitable	Highly suitable
Elevation (m)	715–1545	493–715	361–493	214–361	0–214
Slope (°)	23,5–68,6	14,4–23,4	8,2–14,3	4,1–8,1	0–4
Soil	Arenosol, Calcaric Cambis, Ferric Lixisol, Rhodic Ferraloso	Calcic Vertisol, Eutric Leptosol, 0,18–0,30	Stagnic or Hapl, Ferratic Arenosol, Chromic Luvisol	Mollic Fluvisol, Gleysol	Eutric fluvisol, Fluvisol
Stream density	0–0,18	—	0,30–0,39	0,39–0,49	0,49–0,75
Lineaments (m)	0–100	—	—	—	100–70225
Distance to Villages (km)	0–1	>64,4	34,01–64,4	24,1–34,0	1–24,1
Land Use Land Cover	Evergreen forest, Bare Areas, Artificial water bodies	Grassland, Shrub lands, deciduous forest, Thickets	Closed to open forest with shift cultivation, Regularly Flooded shrub lands	Open forest, Aquatic/Regularly flooded	Cultivated area, Natural water bodies, shifting cultivation to open forest
Rainfall (mm)	599,1–672,0	672,0–751,3	751,3–850,4	850,4–964,7	964–1107,9
Distance to Roads (km)	42,3–65,4	28,2–42,3	16,6–28,2	1–16,6	0–1



**Fig. 5.** Standardised criteria for small dam/reservoir site selection.

A low elevation was considered suitable for dam/reservoir siting since it enables the accumulation of precipitated water. Groundwater is also higher at a lower elevation (Fig. 5a). The slope ranged up to 68,9°. The best locations were the ones with gentle slopes, i.e. areas up to 8,1% slope (Fig. 5b). The range of distance to roads for the study area was from 0 to 65.4 km. Areas within 0–1 km were assigned as “Highly suitable” and larger distances were considered from “Suitable” to “Highly unsuitable” (Fig. 5c). A high priority for siting dam/reservoir was given to locations with precipitation ranging from 964 mm to 1107,9 mm (Fig. 5d). Regarding the

lineaments, and because these geological structures can obstruct the normal stream-flow and cause the water reserves to collapse, the areas with or close to lineaments should be excluded from consideration to site a dam/reservoir (Noori, Pradhan, & Ajaj, 2019). For the study area, the more distant a lineament is, the better the location for the dam/reservoir is (Fig. 5e). The proximity of the dams relative to residential areas can facilitate the task of finding a skilled workforce for the construction and maintenance work of the dam/reservoir itself, as well as making the transfer of water less expensive for rural populations (Emamgholi, Shahedi, Solimani, &

Khaledian, 2007; Safavian & Amani, 2015). In this study, the areas closer to the village were classified as the most suitable (Fig. 5f). The increase in vegetation density results in an increase in the loss of interception, retention and infiltration rates, resulting in decreased flow volume. In turn, cultivated fields are suitable for certain types of rainwater harvesting technologies, while the riparian vegetation is not adequate (Mbilyi et al., 2014). In this study, the most suitable LULC considered were the cultivated areas, natural water bodies, and areas shifting cultivation to open forest (Fig. 5g). The most suitable soils for dam/reservoir site locations should have a higher capacity for water retention (Adham, Riksen, Ouessar, Abed, & Ritsema, 2017). For the study area *Mollic fluvisol* and *Gleysol eutric fluvisol* were considered the most suitable because of their low permeability and higher water-holding ability (Othman et al., 2020) (Fig. 5h). For the stream density factor, a high priority was given to the locations where there was a high drainage density (0.79–0.75/km<sup>2</sup>) when compared to areas of low drainage (Fig. 5i).

#### 4.2. Pairwise comparison of criteria

Based on the local experts and decision makers' opinion, a matrix comparison with weight for all criteria was produced and then normalized (Table 5). Stream density was the most important factor (31%). Both distances to villages and roads were considered the least important factors (2%). We found a  $\lambda_{max} = 10.14$ ,  $n = 9$ ,  $CI = 0.1425$  and a  $CR$  of 0.098. Since the  $CR$  obtained was less than 0.1, the judgments of the experts were considered consistent (T. L. Saaty, 2008).

#### 4.3. Suitability map

A suitability map for the dam/reservoir in the semi-arid zone of the Tete province was produced together with a histogram showing area and percentage for the different categories of suitability (Fig. 6). Although five classes of suitability were predefined, the results of the weighted overlay of the criteria revealed only three levels of suitability: "Not suitable", "Modestly suitable" and "Suitable". The suitability classes "Highly unsuitable" and "Highly suitable" were not found.

The "Modestly suitable" class occupies most of the study area (78%). The "Not suitable" class is predominant in the western zone of the study area, covering about 15% of the region, with emphasis on the districts of Cahora Bassa, Magoe and Changara, most likely due to reduced levels of rainfall and predominance of a drainage network with very low water flow. It is also possible to observe that Tete City districts, Marara and Mutarara contain only "Modestly suitable" and "Suitable" classes. The "Suitable" class only occupies 7% of the region. The individual analysis of the districts shows that Mutara, Doa, Moatize, Magoe and Cahora-Bassa are the districts with the highest coverage of suitable areas, in contrast to the

districts of Marara, Changara and Tete city that have a lower coverage in this class. The comparative analysis by district reveals that although all districts have most of their area classified as "Modestly suitable", the districts of Moatize, Magoe and Chiuta are the ones with the largest proportional area in this class (Fig. 7).

#### 4.4. Analysis of current and future situation

Recent data provided by AraZambeze (ARAZAMBEZE, 2020) indicates that the study area has 38 abandoned dams/reservoirs built with concrete and mortar stone, spatially distributed by the districts of Changara (15), Marara (11), Chiuta (4), Cahora-Bassa (3), Magoe (2), Moatize (2) and Doa (1). The spatial overlay of the abandoned dams and the streams order layers over the suitability level map shows that 35 out of the 38 abandoned dams were in the areas considered as modestly suitable, two dams were in not suitable areas, and only one abandoned dam was in a suitable area. All overlapping points coincide with areas with a stream order of less than 5, i.e., a very low runoff (Fig. 8).

Currently, the region has 37 dams in operation located in the districts of Changara (19), Marara (7), Magoe (5), Cahora Bassa (4), Chiuta (1), and Moatize (1). As shown in Fig. 8, Changara and Marara districts, in the central area of the study area, have the largest number of dams (70.2%), whereas in the eastern districts Doa and Mutarara there is no operational dam. It is also noted that of 37 dams/reservoirs in operation, 78% overlap with the modestly suitable zones, 16.2% are in suitable areas and 5.4% are in not suitable areas. Most of these dams/reservoirs are found in rivers with little flow (stream order less than 5). To increase the number of dams/reservoirs to improve water availability to local communities in the dry season, different governmental entities and NGOs have financed the construction of new dams in the study area. Presently, 15 irrigation dams are under construction, located in the districts of Changara (4), Cahora Bassa (3), Moatize (3), Chiuta (2), Doa (1), Magoe (1), Marara (1). The overlay of these dams with the suitability map show that three dams are in areas considered "Suitable", 11 are in "Modestly suitable" areas and only one dam is in a "Not suitable" zone. Only two dams will be built in a stream order greater than 4 (Fig. 9).

### 5. Discussion

#### 5.1. Main findings and contribution

This paper contributes with a case study for locating the best places for building small dams/reservoirs in a semi-arid region of Mozambique using a GIS-based MCE approach with an AHP. We found that the stream density (31%), rainfall (24%), and lineaments (11%) were the most critical factors in determining the location of these infrastructures according to local expert knowledge. These factors have also been identified in previous studies as the most important ones (Al-Ruzouq, Shanableh, Yilmaz, et al., 2019; Elbeih, 2015). The study also compared the resulting suitability map with current and abandoned dams/reservoirs. This analysis showed that most of the study area falls inside modestly suitable areas (78%), 15% are in not suitable areas, and only 7% of the area is suitable for dam/reservoir construction confirming that in this area the rainfall regime is very low and with severe drought. According to the interviewed experts from AraZambeze, the lack of water in most of the year, silting, rupture, and erosion are the main causes of these dams' abandonment. The overlay of the layers of the dams/reservoirs that were abandoned (92%), operational (78%), and planned (or under construction) (73%) with the suitability map shows that most of these are in modestly suitable areas. This finding suggests that the decision to construct dams/reservoirs may not have

**Table 5**

Normalized pairwise comparison (1: Slope; 2: Elevation; 3: Stream Density; 4: Land Use Land Cover; 5: Soil; 6: Distance to Roads; 7: Rainfall; 8: Distance to Villages; 9: Lineaments).

Criteria	1	2	3	4	5	6	7	8	9	Weight
1	0.05	0.05	0.04	0.07	0.13	0.14	0.05	0.13	0	8%
2	0.05	0.05	0.05	0.07	0.13	0.1	0.05	0.13	0	7%
3	0.39	0.36	0.33	0.5	0.3	0.16	0.29	0.17	0.3	31%
4	0.05	0.05	0.05	0.07	0.17	0.12	0.1	0.09	0.2	10%
5	0.02	0.02	0.05	0.02	0.04	0.14	0.07	0.09	0.1	6%
6	0.01	0.01	0.04	0.01	0.01	0.02	0.03	0.02	0	2%
7	0.29	0.31	0.33	0.21	0.17	0.16	0.29	0.17	0.3	24%
8	0.01	0.01	0.04	0.01	0.01	0.02	0.03	0.02	0	2%
9	0.15	0.15	0.08	0.04	0.04	0.16	0.1	0.17	0.1	11%



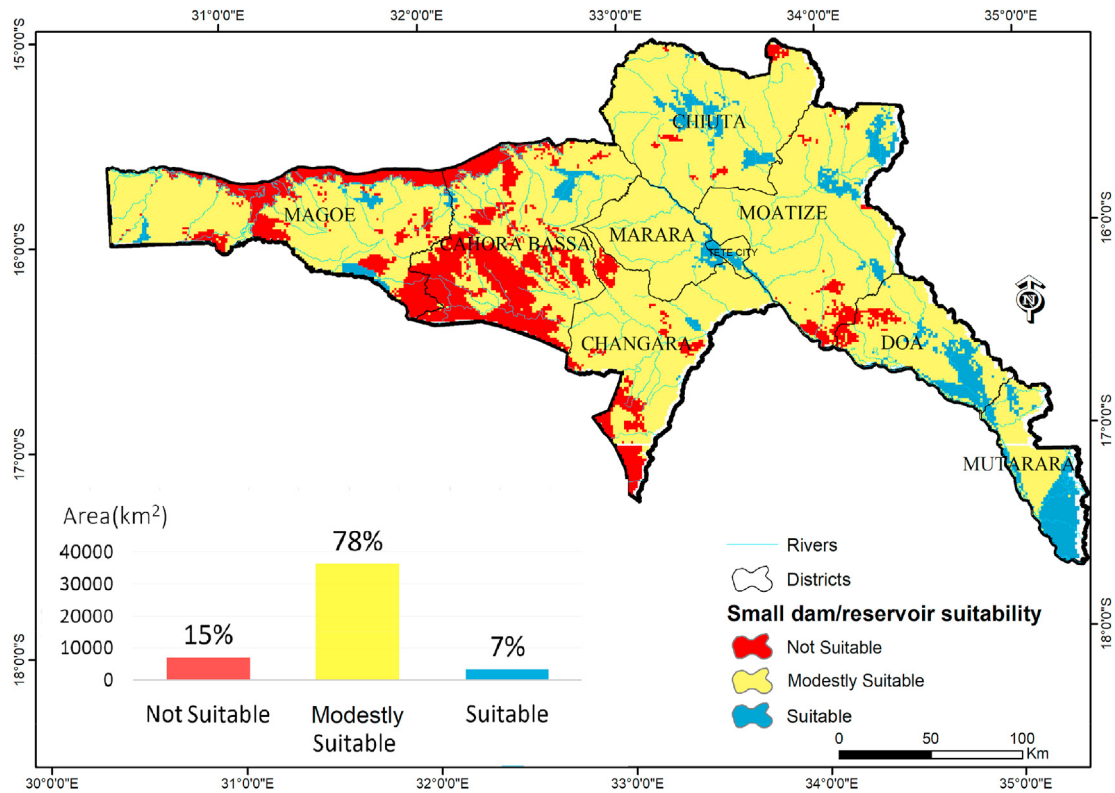


Fig. 6. Small dam/reservoirs suitability categories for the study area.

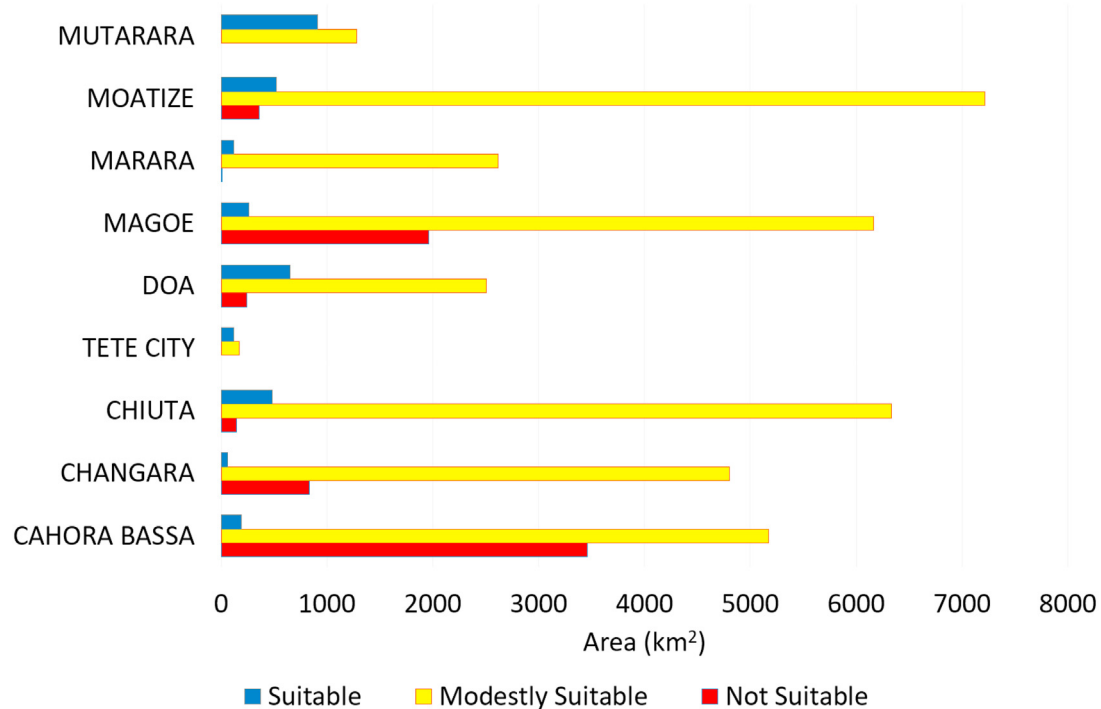


Fig. 7. Level of suitability per district.

considered the most critical suitability factors identified in this study. Since most of the dams/reservoirs still in operation are also in modestly suitable areas, the suitability criteria used may not fully explain whether these infrastructures are still in operation. It may

be possible that the low suitability of a site may have contributed to the abandonment. The full understanding of finding out why so many dams/reservoirs failed seems important before building new ones and requires further analysis with more data and/or additional

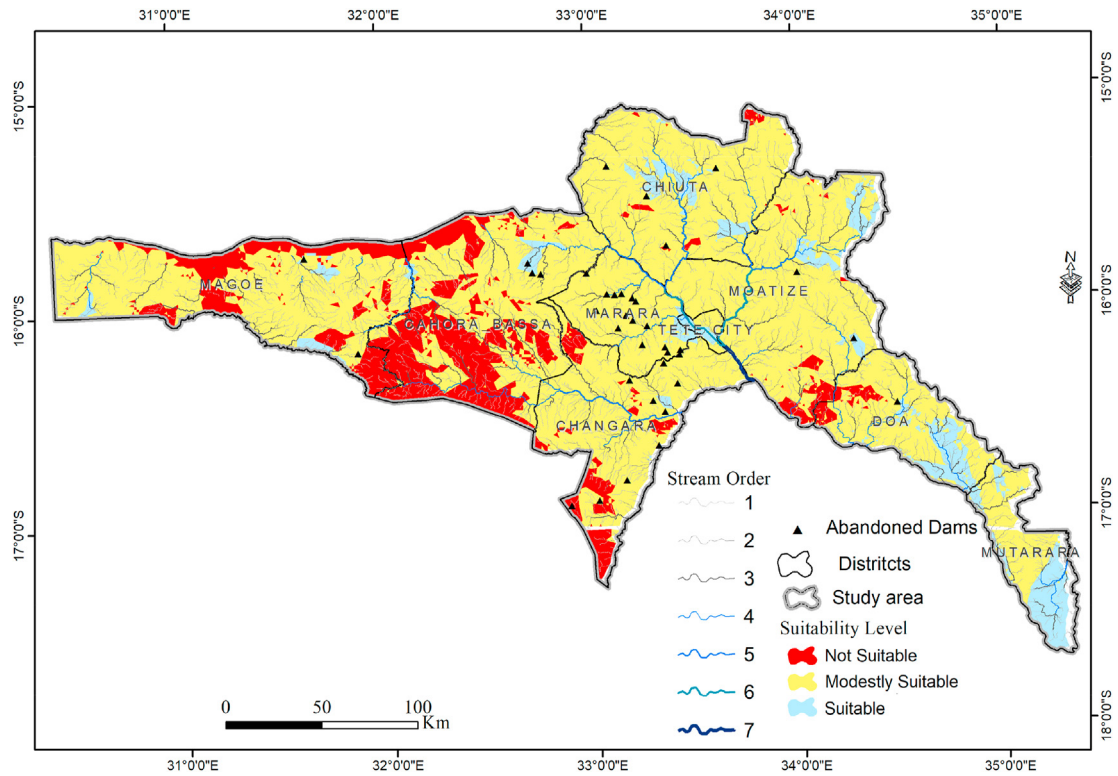


Fig. 8. Abandoned dams/reservoirs overlaid with suitability map and streams.

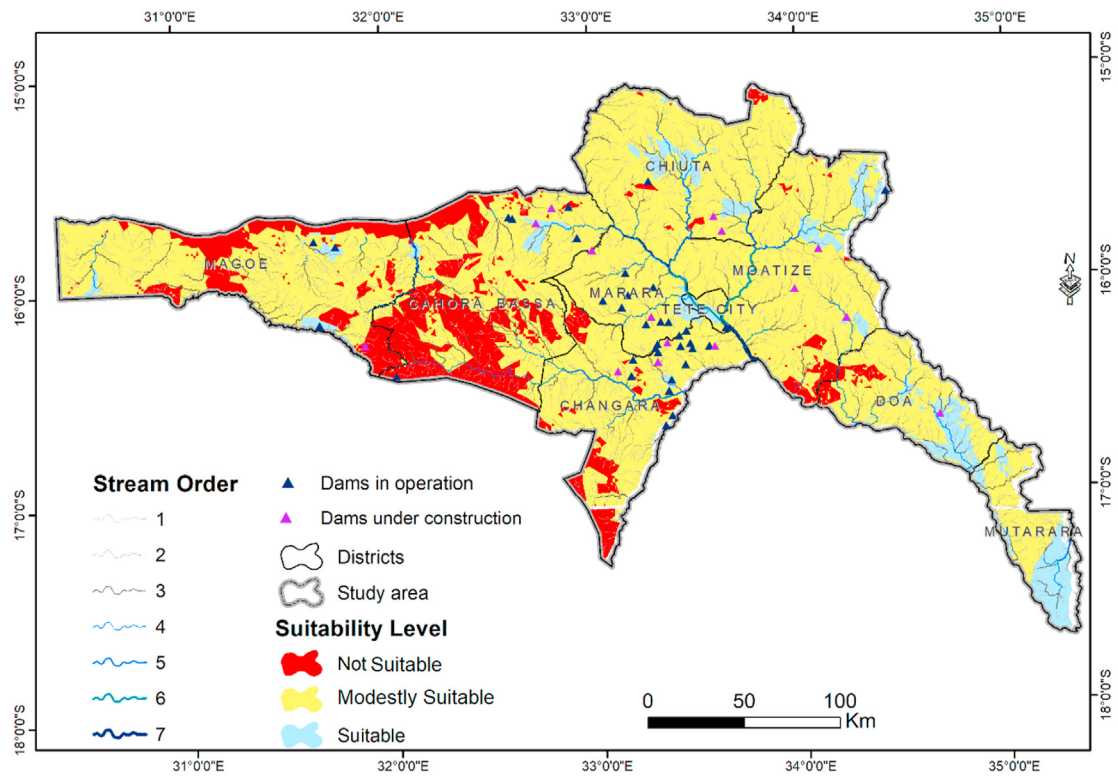


Fig. 9. Geographic location of dams in operation and under construction.

criteria.

## 5.2. Limitations and future developments

The results need to be interpreted with caution since there are limitations that should be considered in future developments of this study. For instance, the MCE modeling approach followed used WLC, which is an additive model that should, ideally, only use independent criteria (Karlsson et al., 2017). Otherwise, some of the factors used may be correlated, resulting in double-counting (Karlsson et al., 2017). However, as Malczewski (2000) pointed out, the requirements of decomposability and non-redundancy are difficult to justify in spatial decision problems. Future versions of this study should incorporate a strategy to avoid redundancy, such as the factor interaction method (A., M., Kheir, & C., 2001).

Another limitation was the lack of a sensitivity analysis. Despite not being so commonly used in suitability analysis (Delgado & Sendra, 2004), a sensitivity analysis was not implemented. We could have varied the weights of the criteria to test if these significantly changed the results obtained. However, in this study, we wanted to incorporate the knowledge of credible local experts who have unique technical and local knowledge about the study area; three of them work for the Regional Water Administration and one has worked as a hydraulic engineer in an infrastructure building international company operating in Mozambique. Since AHP judgments were considered consistent, and the suitability model's results were validated by the abandoned dams/reservoirs, this option was not further explored.

The number of experts who participated in this study is low as in other previous studies with AHP (Alemdar, Kaya, & Çodur, 2020; Dash & Sar, 2020; Peterson, Silsbee, & Schmoldt, 1994). Although, it would have been desirable to have more experts to possibly bring more relevant knowledge for the decision process, we had to work with the ones we could find for this study area in Mozambique. Nevertheless, a variability and confidence analysis regarding experts' level of knowledge about each criterion should be envisaged in future versions of this study to bring more credibility to the results (Campagne, Roche, Gosselin, Tschanz, & Tatoni, 2017; Elliott et al., 2020). The dams/reservoirs' location would also benefit from a participatory process with stakeholders (Luijten, Knapp, Sanz, & Jones, 2003; Roozbahani, Abbasi, Schneider, & Hosseinfard, 2020). Thus, for the process to be considered community property, it is recommended to conduct fieldwork for community consultation to assess the population's point of view regarding the construction of the dams/reservoirs in the proposed locations. Local communities and other stakeholders' involvement in water projects is crucial as it brings transparency, acceptability, support, and ensures the sustainability of the process (Dungumaro & Madulu, 2003). This element will prevent, for instance, land-use conflicts and will involve populations in the resolution of possible problems, such as erosion, siltation, and others. Future works aiming to improve results' quality and reliability should consider participatory events with all relevant stakeholders.

Aspects, such as local knowledge and the ability to maintain the dam/reservoir or access to better alternative water sources could also cause dam/reservoir failure. A more structured in-depth research using the same suitability criteria to determine the exact reasons for abandoning dams/reservoirs could have been done. This action would enable verifying if the criteria used for the suitability analysis were well chosen. Unfortunately, we did not have data to check precisely why each dam/reservoir failed. We only had information about their location and operational status. To pinpoint why each specific dam failed would involve field work which we could not do due to lack of resources. However, future versions of this work should include this aspect since it would validate the results more consistently.

Another possible improvement for this study is data. For

instance, we could use locally measured rainfall data instead of interpolated global data (Fick & Hijmans, 2017), which is known to have substantial discrepancies (Faye, Herrera, Bellomo, Silvain, & Dangles, 2014). Although we tried to use the best possible data, future versions of the suitability model will benefit from more accurate datasets when these are made available.

## 6. Conclusion

Identifying suitable areas for building small dams/reservoirs is essential for the study area, a semi-arid region with important water deficits. The approach followed in this study based on GIS-based MCE together with an AHP enabled us to obtain information about the relevant variables (i.e., slope, elevation, rainfall, stream density, lineaments, soil, land-use land cover and two socioeconomic factors, distance to roads and distance to villages) to create a small dam/reservoir suitability map for the region of Tete, Mozambique. Results show that most of the currently operating and planned small dams/reservoirs are located in modestly suitable areas. This means that the main location factors for building a dam are not being considered, reinforcing the need to use a spatial MCE approach. This information raises concerns about the future effectiveness of these infrastructures and should be carefully analyzed by planners to better address the population's water needs in the region. The methodology is flexible enough to easily consider additional criteria, experts/stakeholders, and up-to-date data in the process of deciding where to locate these infrastructures in semi-arid regions or any other locations facing water scarcity problems.

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